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GFO On-Orbit Altimeter Noise Assessment

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Litton
TASC

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1. INTRODUCTION

The purpose of this report is to present the results of an analysis of the *white noise level* in Geosat Follow-On (GFO) altimeter data. The Repeat-Track Method was used to determine noise level. This approach was developed at TASC and has been used to quantify noise levels of all previous satellite altimeter missions (Refs. 1-6). The GFO altimeter was designed to have an RMS white noise level of less than 3.5 centimeters for significant wave height less than 2 meters. *The results of the analysis presented here show that the GFO altimeter meets this specification.*

NASA/WFF provided the 26 track pairs of 1-Hz GFO altimeter data used in this analysis. The track locations are shown on the map in Fig. 1-1. Significant wave height (SWH) along these tracks ranges from approximately 1 meter to 6 meters, providing a good sampling of calm to rough sea surface conditions. Using the Repeat Track Method, we computed noise levels for each of the 26 track pairs. These results are tabulated and plotted. In addition to using the Repeat-Track Method, we analyzed each track individually using a variation on a filtering algorithm previously developed by TASC (Refs. 7-8). The previous approach, called Equalize and Filter (EAF, Ref. 7), was originally developed for 10-Hz data, along single (not repeat) tracks. The *new approach,* developed in this work, is a simplified version of EAF that is applied to individual tracks of 1-Hz data, and involves only high-pass filtering (without the prior "equalization" filter). Noise-level estimates obtained by the new filtering approach agree very well with the results from the more difficult to implement Repeat-Track Method. We also applied the original EAF procedure to a single track of 10-Hz GFO data, and the computed white noise level also agrees with the repeat-track analysis.

Our new results using high-pass filtering of 1-Hz data are particularly encouraging. We have demonstrated the robust nature of this simplified, single-track analysis approach that avoids the need to compute power spectra. A potential application of our new algorithm is to monitor altimeter noise on single tracks, since this could be applied in near real time and would not require environmental corrections to the raw altimeter data.

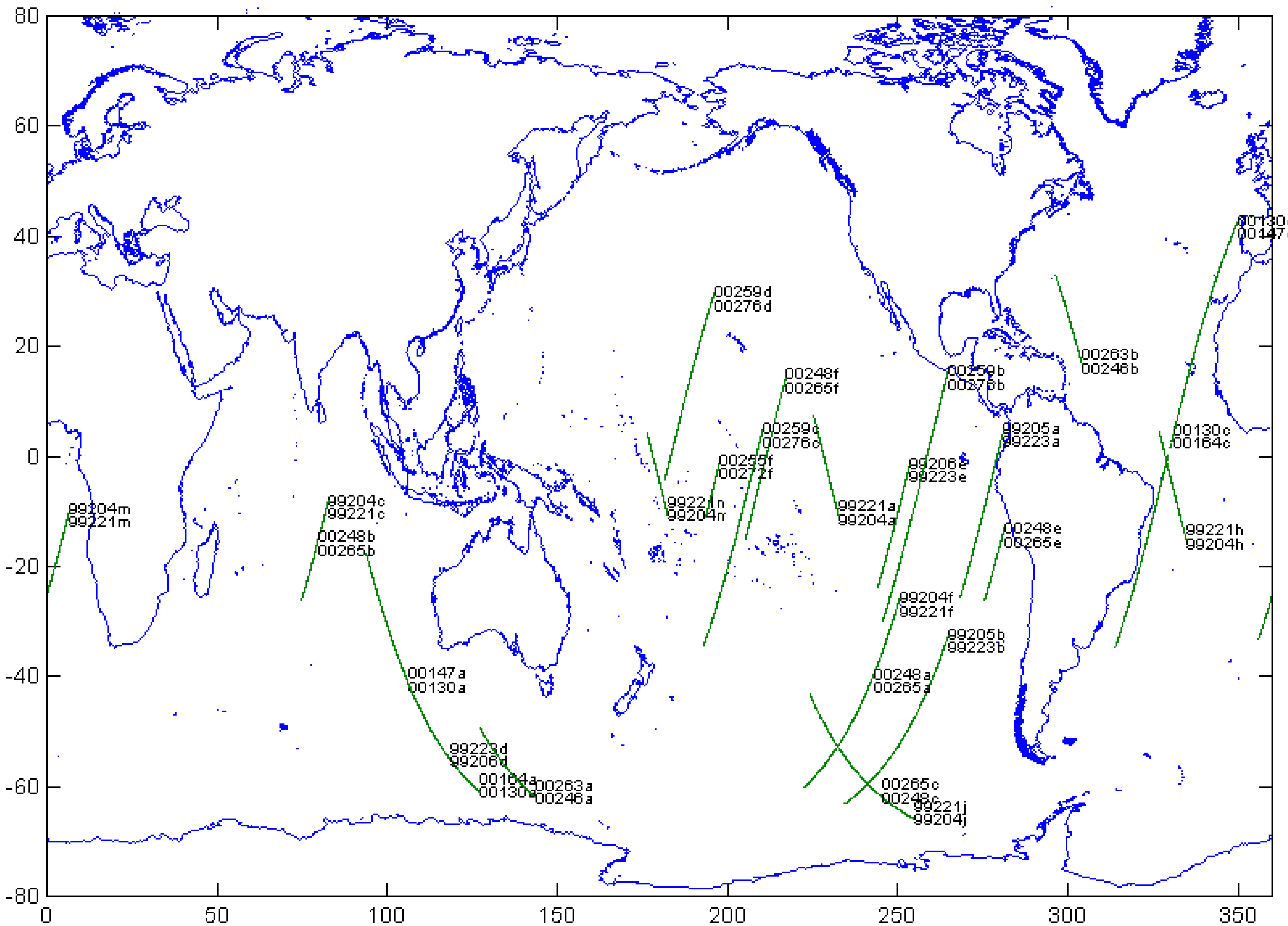


Figure 1-1 GFO track pairs used in the repeat track analysis. Track labels are in the format *yyddds* where *yy* indicates the calendar year in which the data were collected, *ddd* the calendar day, and *s* indicates a particular segment of track (a through z).

2. REPEAT-TRACK ANALYSIS

Sea surface height data corrected for instrumental and environmental effects were used in this analysis. The data are provided at a sample spacing of approximately 1 sample-per-second. Each pair of repeat tracks is aligned by finding the closest pair of measurement points, then the two time series are differenced. (Sea surface heights are not interpolated to a common reference track to avoid the smoothing associated with interpolation). Height differences that exceed three times the standard deviation are removed, and small gaps in the time series are filled by linear interpolation. The resulting difference time series contains time-varying signals caused by mesoscale oceanography, long-wavelength orbit errors, and uncorrelated noise. A power spectral density (PSD) of the height differences is computed and divided by 2 to obtain the noise PSD. The white noise power spectral density level is estimated by averaging the PSD at frequencies between 0.3 and 0.5 Hz. The RMS white noise level for 1 Hz data is then obtained by integrating the estimated noise PSD level between 0 and 0.5 Hz (Ref. 6). See Appendix A for plots of the GFO data, the repeat track differences, and the noise PSDs with the RMS white noise levels identified.

The results of the repeat-track analysis are listed in Table 2-1. Values of RMS noise level range from 1.9 to 5.0 cm. The noise level is sensitive to significant wave height (SWH), with larger noise values associated with larger significant wave heights. This relationship is illustrated in a plot of noise level versus SWH (Fig. 2-1). Data from three different time spans are indicated by different colored symbols. The most recent data (most up-to-date GFO GDR processing) are plotted with red asterisks, but these are indistinguishable from the earlier noise estimates. The best-fit line to the 26 noise estimates is also plotted. These results show that the GFO noise level is less than 2.7 cm for significant wave heights less than 2 meters, thereby meeting the system design specifications.

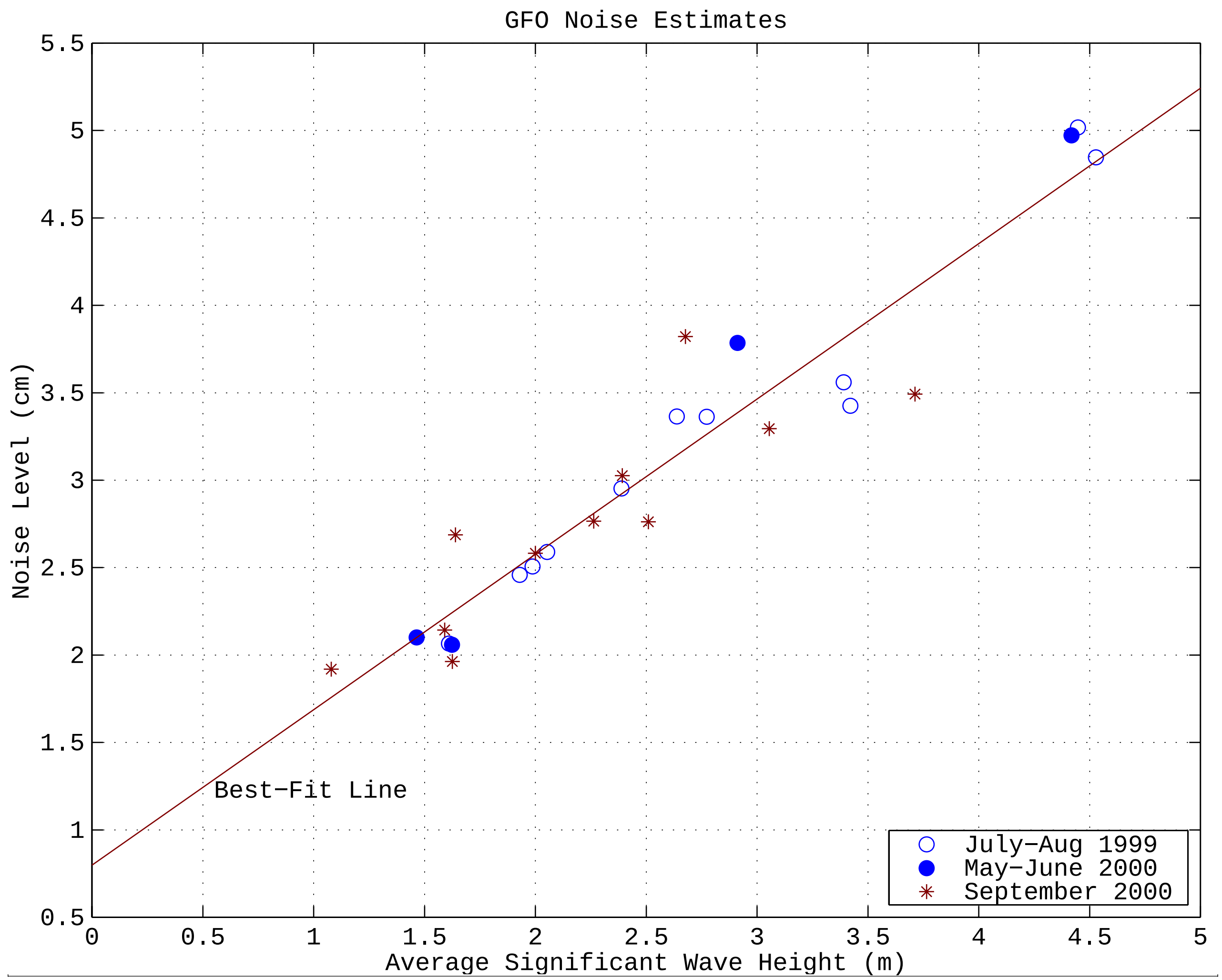


Figure 2-1 Repeat-track estimates of GFO white noise level plotted versus significant wave height. GFO data from different time periods are indicated by different symbols.

Track1	Track2	# Outliers	Samples in Pair	Average SWH (m)	Noise level (cm)
99204a	99221a	0	337	1.93	2.46
99204c	99221c	1	328	2.77	3.36
99204f	99221f	0	429	3.39	3.56
99204h	99221h	0	367	2.05	2.59
99204j	99221j	0	285	4.53	4.85
99204m	99221m	0	429	2.64	3.36
99204n	99221n	0	269	1.61	2.07
99205a	99223a	3	551	1.99	2.51
99205b	99223b	3	612	3.42	3.43
99206d	99223d	2	825	4.45	5.02
99206e	99223e	1	408	2.39	2.95
00130a	00164a	0	381	4.42	4.97
00130a	00147a	0	353	2.91	3.78
00130c	00164c	73	718	1.46	2.10
00130c	00147c	2	690	1.62	2.06
00246a	00263a	1	270	3.71	3.49
00246b	00263b	2	305	1.08	1.92
00248a	00265a	0	407	2.51	2.76
00248b	00265b	0	303	2.39	3.03
00248c	00265c	0	404	3.06	3.29
00248e	00265e	1	235	2.68	3.82
00248f	00265f	1	537	1.59	2.14
00255f	00272f	0	183	1.63	1.96
00259b	00276b	0	820	2.00	2.58
00259c	00276c	1	713	2.26	2.77
00259d	00276d	0	613	1.64	2.69

Table 2-1 RMS white noise level computed from GFO repeat track pairs

3. FILTERING ANALYSIS

TASC has been investigating algorithms that can provide noise level estimates that are comparable to the Repeat-Track Method, but that are simpler to implement. The Repeat-Track Method has several disadvantages (Ref. 7), one of which is the need for fairly long, continuous time series to compute the PSD. The purpose of the repeat track pair is to remove the geoid signal so that the time series of time-varying noise is revealed. Experience has shown that *white noise* dominates the altimeter time series at the shortest wavelengths. This suggests an alternative noise measurement algorithm that can be applied to single tracks of data. Previously TASC developed the Equalize and Filter (EAF) algorithm (Ref. 7) that works by highpass filtering 10-Hz data. We now have demonstrated a new and simpler filtering algorithm that works with 1-Hz data.

New Method Using 1-Hz Data: The 1-Hz data analyzed with the Repeat-Track Method were also analyzed using this new and simpler filter method, outlined in the following steps.

1. Highpass filter 1-Hz time series using a 5^{th}-order Butterworth filter (removes the geoid and all long-wavelength environmental effects). The output is highpassed white noise. The RMS of this noise is *proportional* to the RMS of the white noise floor in the original data.
2. Edit to remove outliers and filter startup transients.
3. Compute the RMS value of the resulting time series.
4. Scale the RMS result to compute the inferred RMS white noise level for 1-Hz data. The scale factor is dependent on the filter. For the 5^{th}-order Butterworth filter, scale factors are 1.574, 1.807, and 2.200 for cutoff frequencies of 0.3, 0.35, and 0.4 Hz[1]. The scaled value is comparable to the traditional value derived from repeat-track analysis.

The results of the filtering analysis are shown in Fig. 3-1 for three different cutoff frequencies. The results from the repeat-track analysis are also plotted. There is very close agreement between the two methods, and there is little difference in the results for the three selected frequency cutoffs. These results of the filtering analysis are also listed in Table 3-1. Comparing the values in the third and fourth columns shows how well the two methods agree.

[1] The scale factors are determined numerically by computing the square root of the reciprocal of the integrated Power Gain Function of the Butterworth highpass filter. This is equivalent to the ratio of the standard deviations of an input time series (white noise) and the highpass filtered time series.

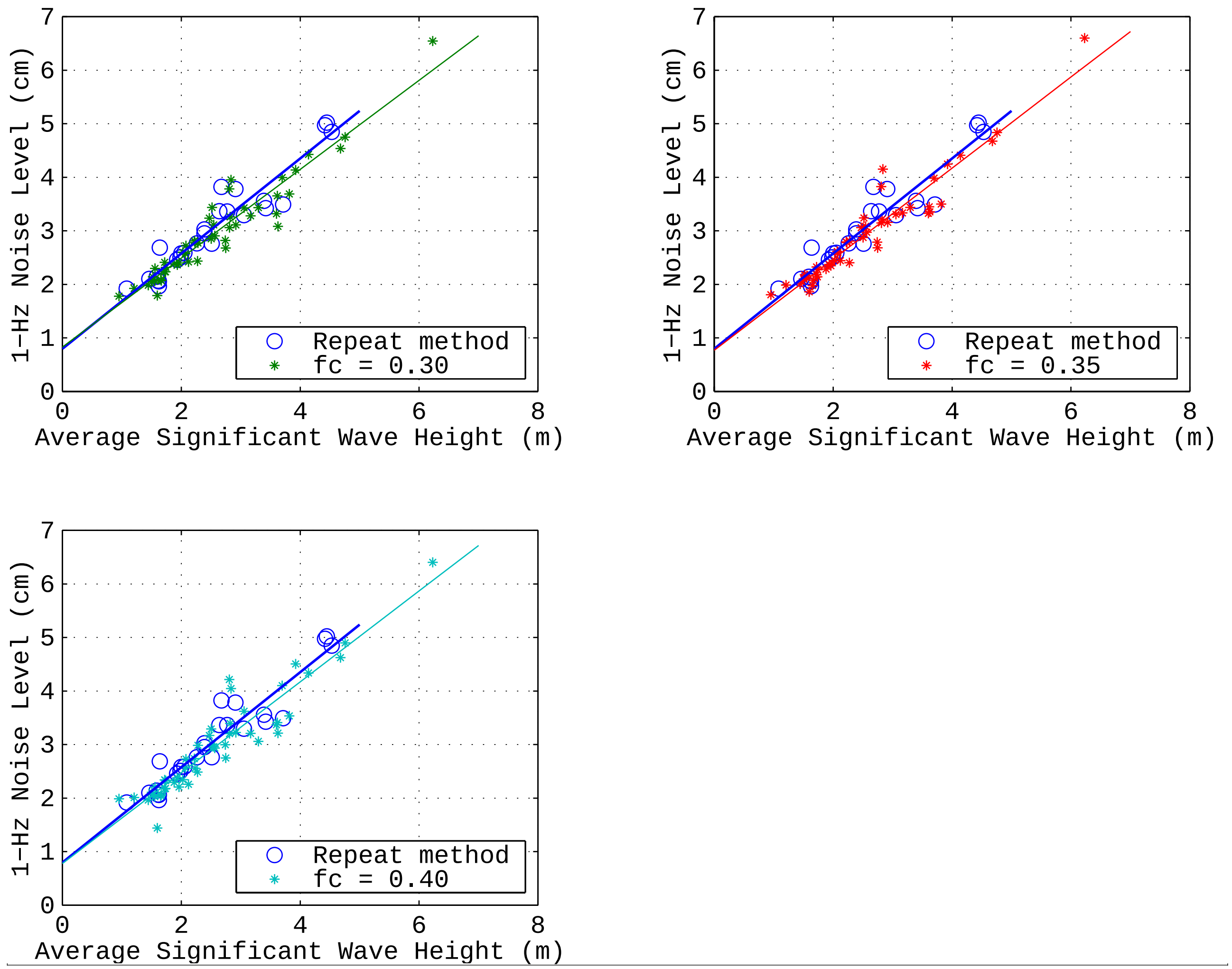


Figure 3-1 Highpass filtering estimates of GFO RMS white noise level for three values of the filter cutoff frequency, 0.3, 0.35, and 0.4 Hz. Repeat-track estimates of RMS white noise level are plotted for comparison. Straight lines are the best fits to the sets of estimates.

GFO Track	SWH (m)	Noise level (cm) Highpass Filter (fc = 0.3 Hz)	Noise level (cm) Repeat-Track Method	Average SWH (m)	Samples in Pair
99204a	2.12	2.42	2.46	1.93	337
99221a	1.74	2.24			
99204c	2.74	2.82	3.36	2.77	328
99221c	2.81	3.78			
99204f	3.16	3.28	3.56	3.39	429
99221f	3.62	3.65			
99204h	2.03	2.60	2.59	2.05	367
99221h	2.08	2.72			
99204j	2.82	3.26	4.85	4.53	285
99221j	6.23	6.54			
99204m	3.06	3.43	3.36	2.64	429
99221m	2.22	2.81			
99204n	1.67	2.07	2.07	1.61	269
99221n	1.56	2.06			
99205a	2.47	3.24	2.51	1.99	551
99223a	1.50	2.05			
99205b	2.92	3.11	3.43	3.42	612
99223b	3.92	4.14			
99206d	4.76	4.75	5.02	4.45	825
99223d	4.14	4.43			
99206e	2.55	3.11	2.95	2.39	408
99223e	2.23	2.78			
00130a	3.70	3.99	4.97	4.42	381
00164a	4.68	4.54			
00130a	3.70	3.99	3.78	2.91	353
00147a	3.63	3.09			
00130c	1.52	2.14	2.10	1.46	718
00164c	1.72	2.41			
00130c	1.52	2.14	2.06	1.62	690
00147c	1.88	2.38			
00246a	3.60	3.32	3.49	3.71	270
00263a	3.82	3.69			
00246b	1.21	1.93	1.92	1.08	305
00263b	0.95	1.78			
00248a	2.27	2.44	2.76	2.51	407
00265a	2.75	2.68			
00248b	2.50	2.85	3.03	2.39	303
00265b	2.28	2.77			
00248c	2.81	3.06	3.29	3.06	404
00265c	3.30	3.43			
00248e	2.84	3.95	3.82	2.68	235
00265e	2.52	3.44			
00248f	1.44	1.98	2.14	1.59	537
00265f	1.74	2.32			
00255f	1.60	1.79	1.96	1.63	183
00272f	1.66	2.09			
00259b	2.07	2.57	2.58	2.00	820
00276b	1.93	2.37			
00259c	1.96	2.40	2.77	2.26	713
00276c	2.56	2.91			
00259d	1.56	2.30	2.69	1.64	613
00276d	1.72	2.24			

Table 3-1 RMS White noise level for GFO track segments computed using a highpass filter, compared to RMS white noise level computed using Repeat-Track Method on track pairs.

Original EAF Algorithm: We had available to us a single track of 10-Hz GFO sea surface height data, provided by Bruce Lunde of the Naval Oceanographic Office. The data are from day 207, year 1999, with about 3700 usable data points. The data were produced prior to February 2000 and, therefore, do not represent the latest GFO GDR data processing (but this should not affect our results since EAF looks at only the highest frequencies). The sea surface heights were analyzed with the original EAF algorithm using a cutoff frequency of 0.5 Hz. The resulting white noise level for this track is 2 cm, and the average significant wave height is 1.2 m. This single EAF result is added to the previous plot showing the results obtained with the Repeat-Track Method, and the 1-Hz filtering method (Fig. 3-2). The RMS white noise level obtained from the EAF algorithm is in agreement with the previous results.

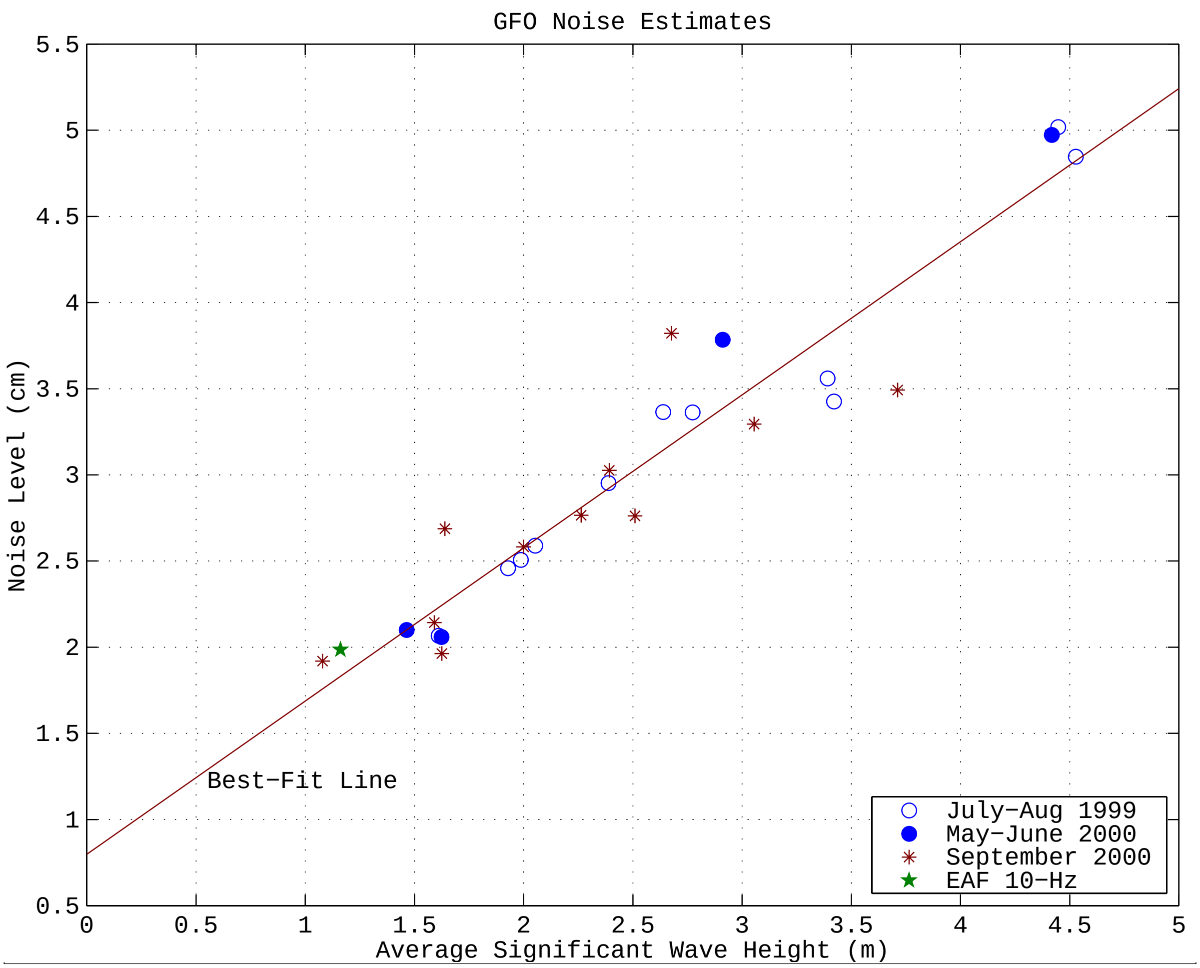


Figure 3-2 EAF estimate of RMS white noise level in GFO data (green star). Repeat-track estimates of RMS white noise level are plotted for comparison.

4. SUMMARY AND CONCLUSIONS

RMS white noise levels for 26 GFO track pairs have been computed using the standard Repeat-Track Method. The noise level increases linearly with increasing significant wave height. For values of significant wave height less than 2.0 m, the maximum observed noise level is 2.7 cm.

RMS white noise levels have also been determined from the 1-Hz GFO data using a simple highpass filtering algorithm, and from a single track of 10-Hz data using TASC s original EAF filtering algorithm. Both of these results closely agree with those obtained from the Repeat-Track Method. This agreement indicates that either of these algorithms may be a good candidate for monitoring altimeter noise levels. The value of the filtering techniques is that they can operate on single tracks of altimeter data, without applying environmental corrections.

A topic that could not be extensively studied is the sensitivity of the filtering algorithms to high-amplitude, short-wavelength geoid signals such as those observed across the mid-Atlantic Ridge. The cutoff wavelength for the highpass filter must be short enough to remove the entire geoid signal, yet long enough to permit a robust estimate of the white noise level. Thus, the highest feasible cutoff frequency for the filter remains to be determined. We may find the EAF algorithm to be the more robust of the two filtering algorithms because the bandwidth of 10-Hz data is larger than that for 1-Hz data, permitting shorter cutoff wavelengths to be used.

APPENDIX A GFO DATA ANALYSIS RESULTS

Plots of the GFO data used in the repeat-track analysis, and the noise process power spectral density (PSD) for each of the 26 track pairs are presented in this appendix. For each track pair, the aligned sea surface heights, corrected for environmental effects, are plotted as shown in Fig. A-1. Beneath this, the difference time series (minus a constant) is plotted, followed by plots of the significant wave height for each track. Presented next is a plot of the noise PSD, and the calculated white noise level (Fig. A-2), and for comparison, PSDs of the sea surface height for each track. This set of plots is presented for each track pair, in the same order listed in Table 2-1.

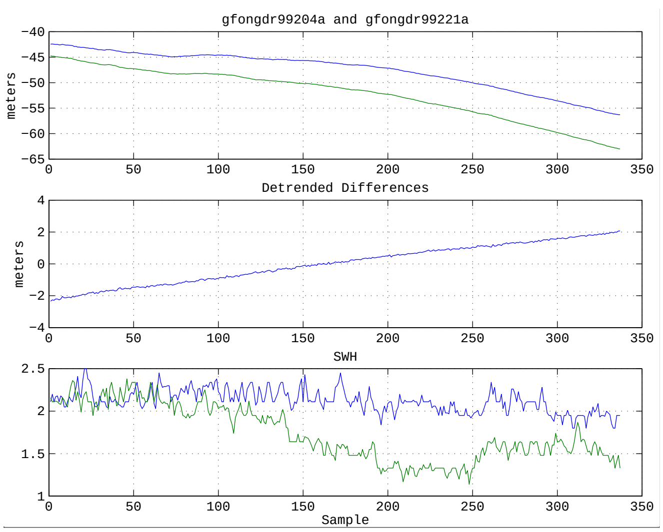


Figure A-1 Sea surface heights for GFO track 99204, segment a (blue), and GFO track 99221, segment a (green), aligned and corrected for environmental effects, detrended differences (only a mean is removed), and significant wave height.

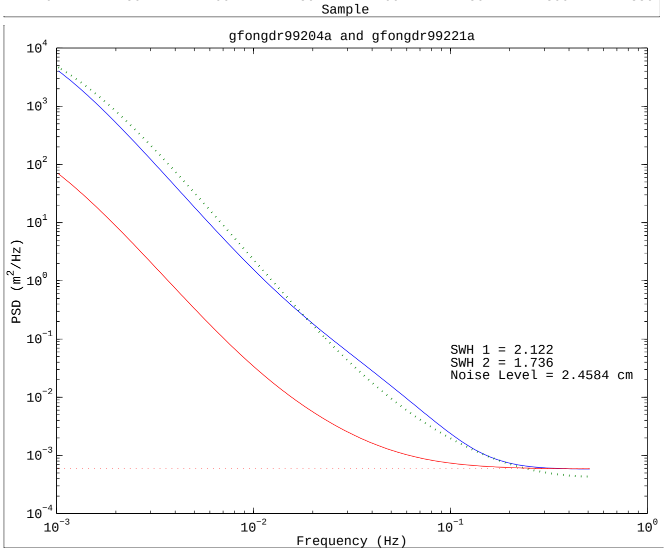
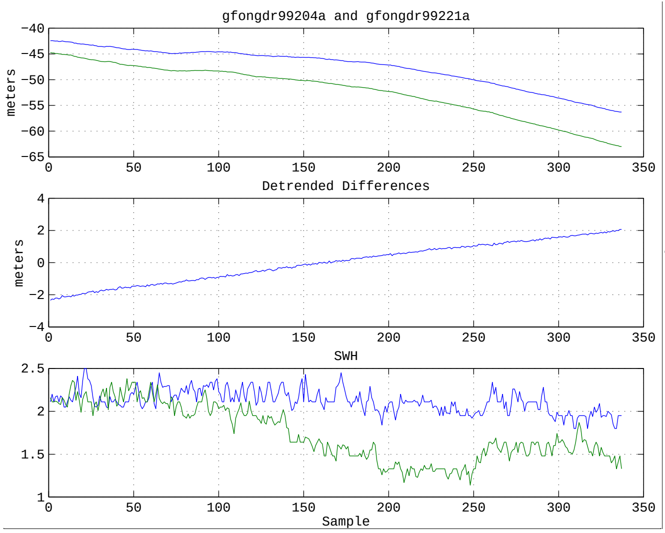
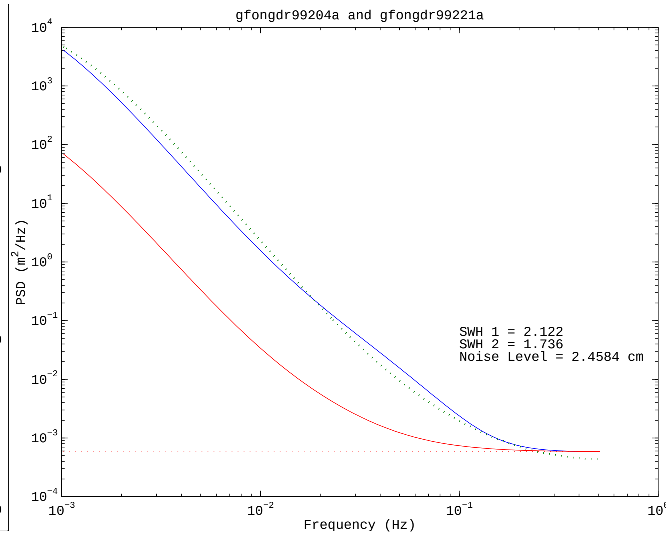
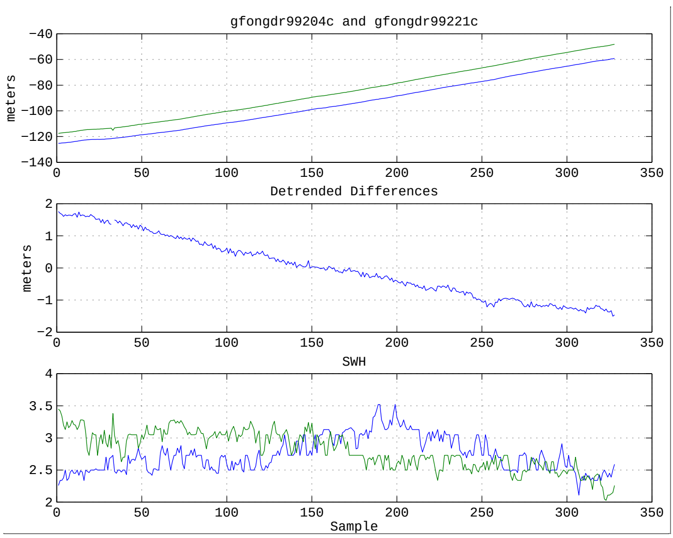
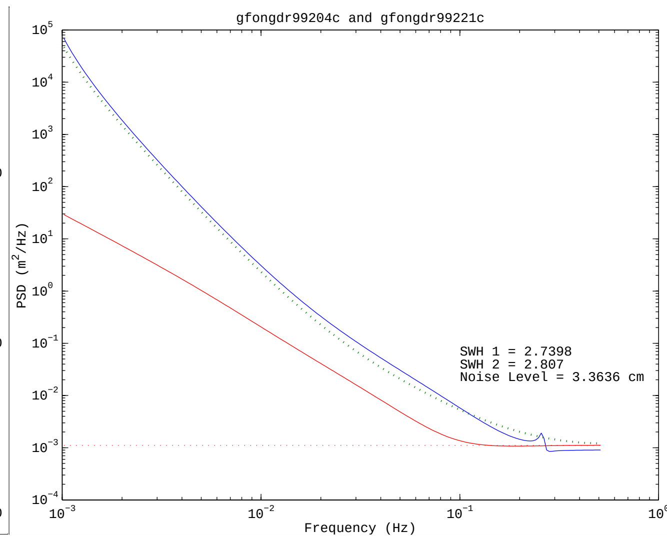


Figure A-2 Power spectral density plot of the noise process and the white noise floor (red), and sea surface height PSDs for tracks 99204, segment a, and GFO track 99221, segment a (blue and dotted green).


gfongdr99204a and gfongdr99221a
meters
Detrended Differences
meters
SWH
Sample


gfongdr99204a and gfongdr99221a
PSD (m^2/Hz)
SWH 1 = 2.122
SWH 2 = 1.736
Noise Level = 2.4584 cm
Frequency (Hz)


gfongdr99204c and gfongdr99221c
meters
Detrended Differences
meters
SWH
Sample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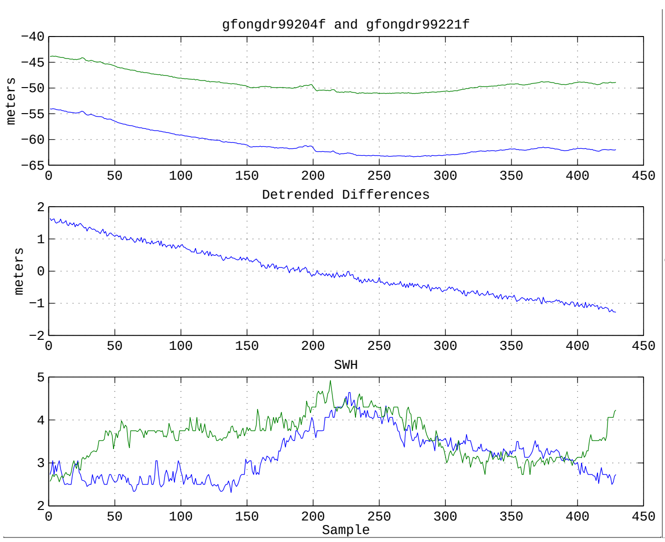
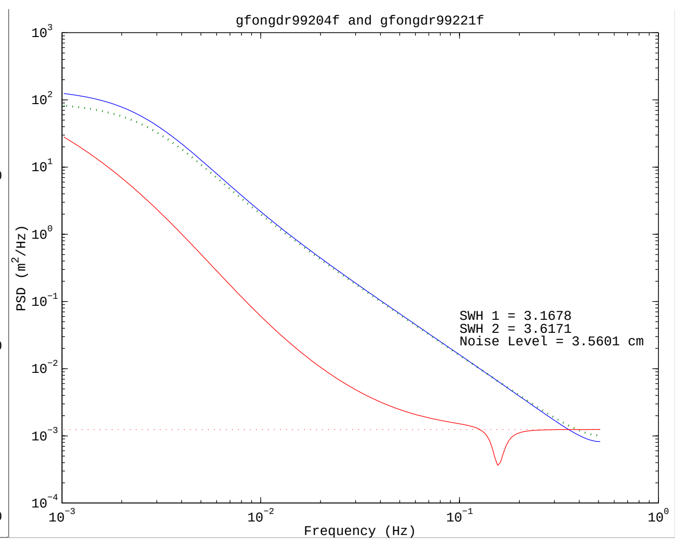
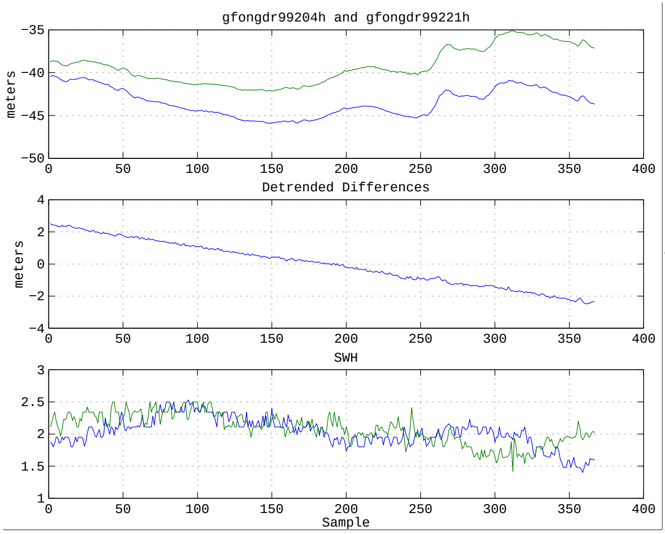
PSD (m^2/Hz)
SWH 1 = 2.7398
SWH 2 = 2.807
Noise Level = 3.3636 cm
Frequency (Hz)


gfongdr99204f and gfongdr99221f
meters
Detrended Differences
meters
SWH
Sample


gfongdr99204f and gfongdr99221f
PSD (m^2/Hz)
SWH 1 = 3.1678
SWH 2 = 3.6171
Noise Level = 3.5601 cm
Frequency (Hz)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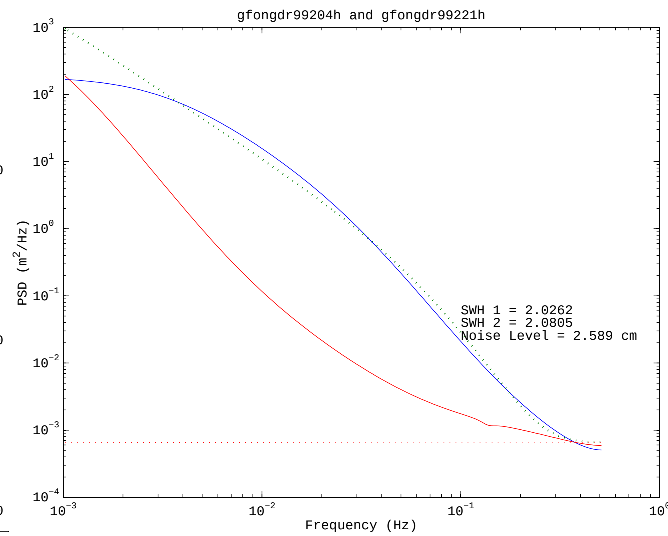
meters
Detrended Differences
meters
SWH
Sample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PSD (m²/Hz)
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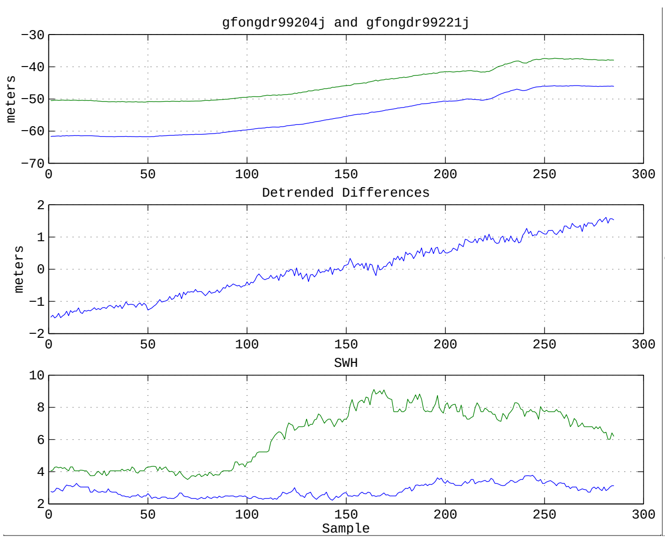
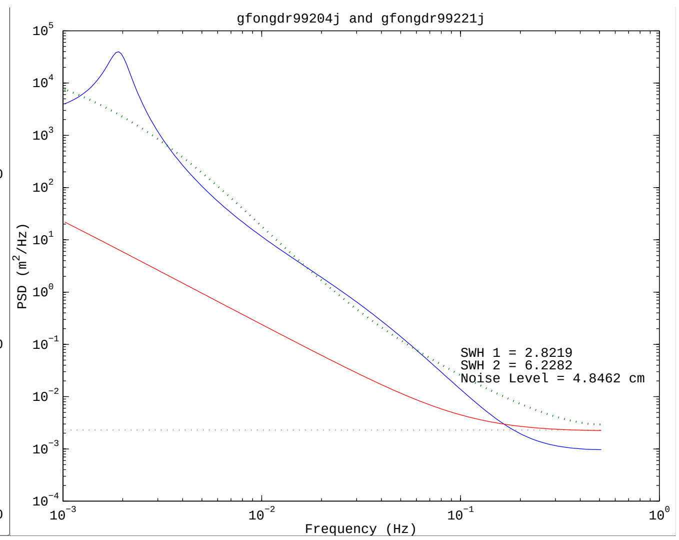
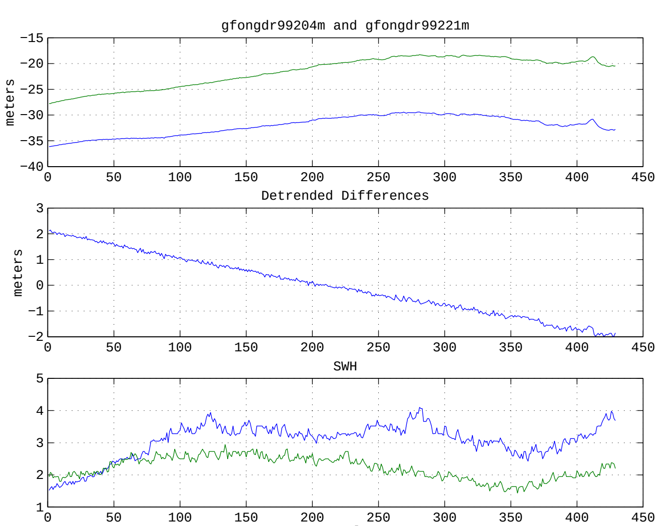
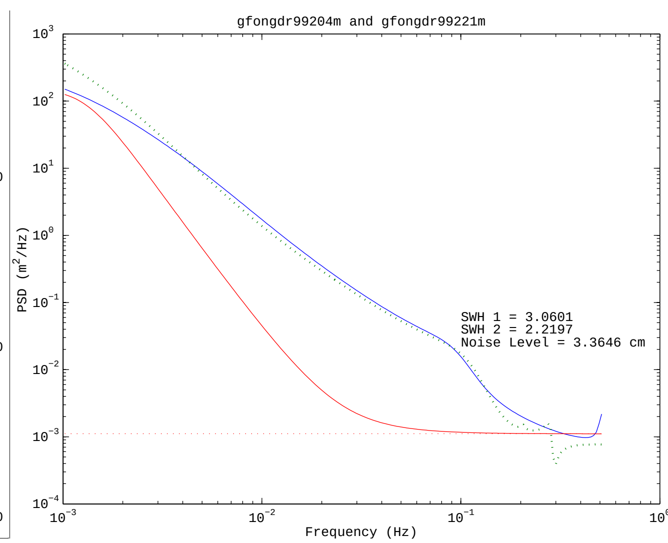
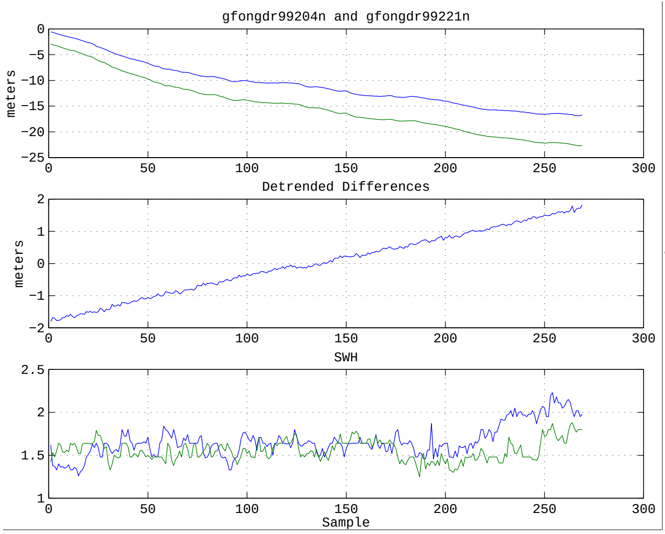
SWH 2 = 2.0805
Noise Level = 2.589 cm
Frequency (Hz)

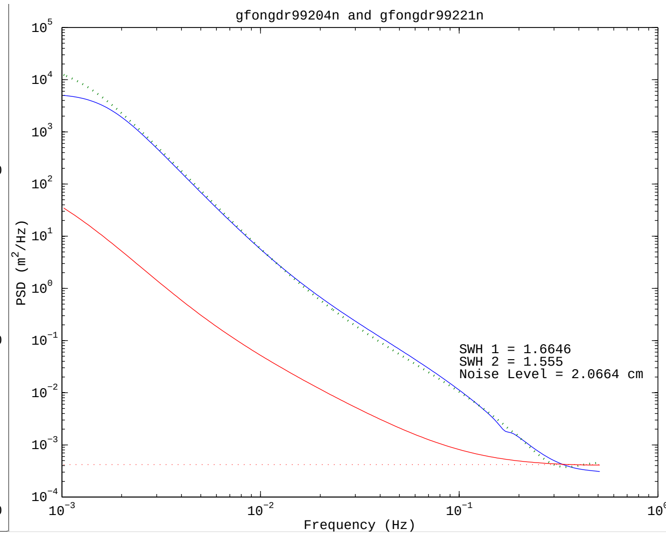

gfongdr99204j and gfongdr99221j
meters
Detrended Differences
meters
SWH
Sample

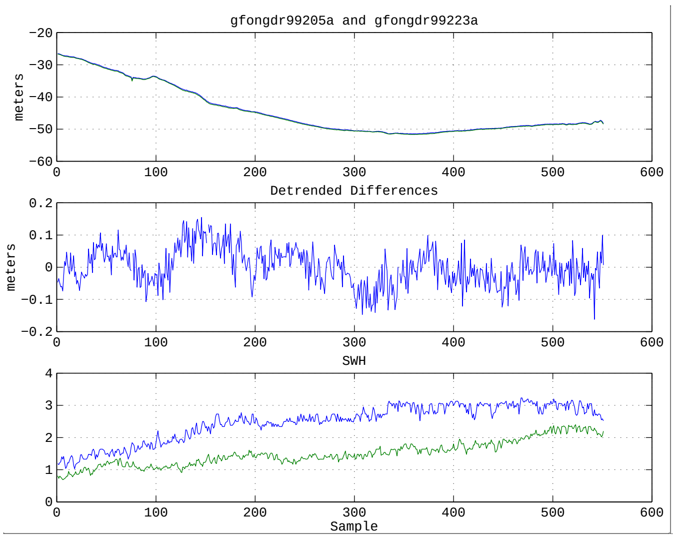

gfongdr99204j and gfongdr99221j
PSD (m²/Hz)
SWH 1 = 2.8219
SWH 2 = 6.2282
Noise Level = 4.8462 cm
Frequency (Hz)

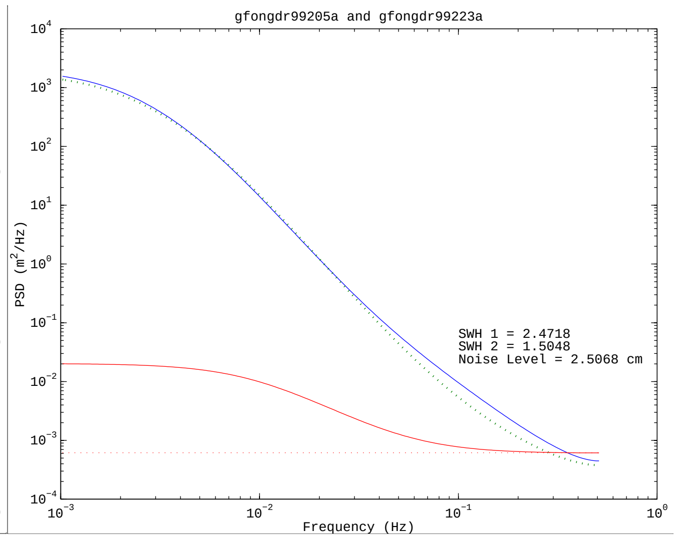

gfongdr99204m and gfongdr99221m
meters
Detrended Differences
meters
SWH
Sample


gfongdr99204m and gfongdr99221m
PSD (m²/Hz)
SWH 1 = 3.0601
SWH 2 = 2.2197
Noise Level = 3.3646 cm
Frequency (Hz)


gfongdr99204n and gfongdr99221n
meters
Detrended Differences
meters
SWH
Sample


gfongdr99204n and gfongdr99221n
PSD (m^2/Hz)
Frequency (Hz)
SWH 1 = 1.6646
SWH 2 = 1.555
Noise Level = 2.0664 cm


gfongdr99205a and gfongdr99223a
meters
Detrended Differences
meters
SWH
Sample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PSD (m^2/Hz)
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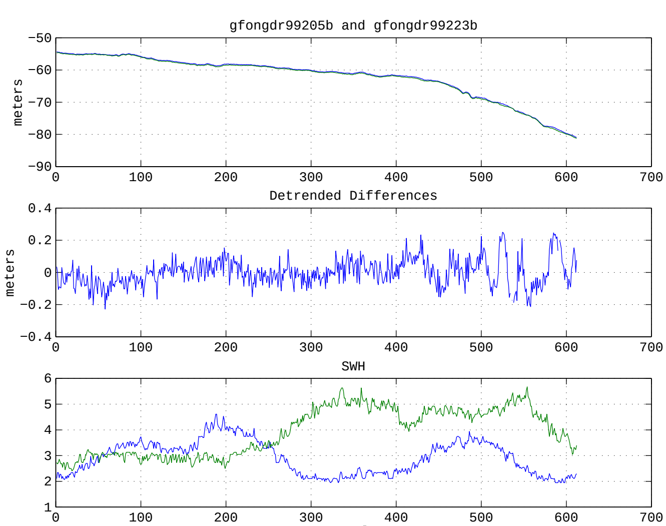
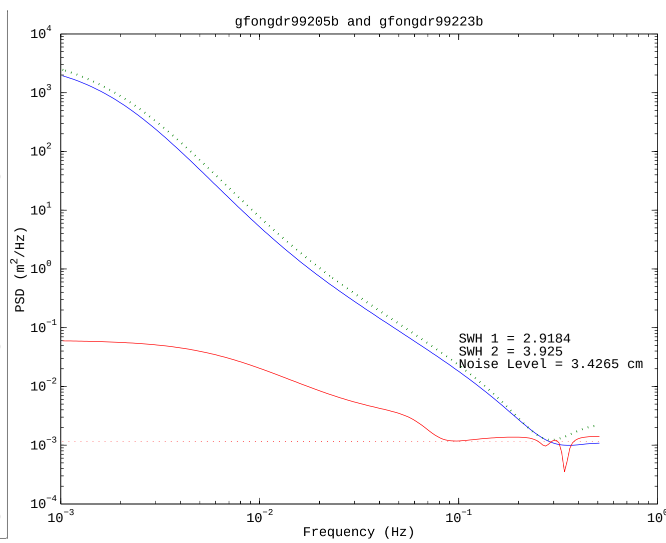
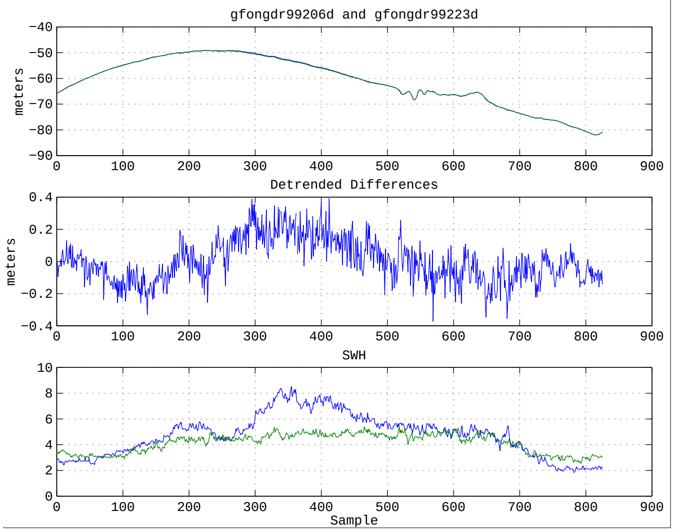

gfongdr99205b and gfongdr99223b
meters
Detrended Differences
meters
SWH
Sample


gfongdr99205b and gfongdr99223b
PSD (m^2/Hz)
Frequency (Hz)
SWH 1 = 2.9184
SWH 2 = 3.925
Noise Level = 3.4265 cm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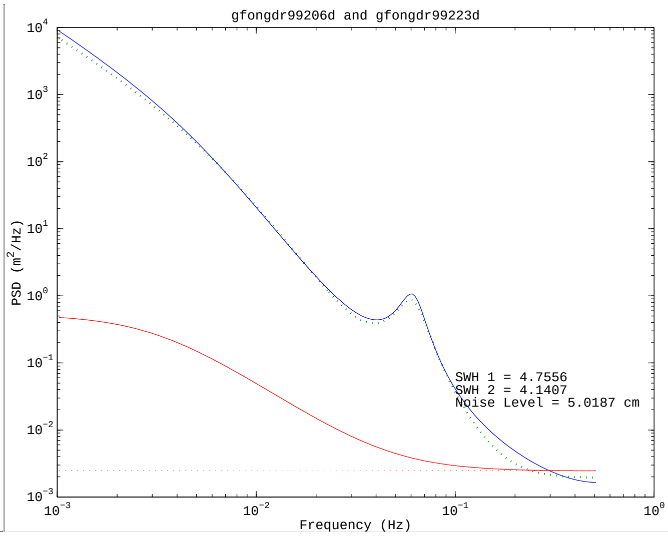
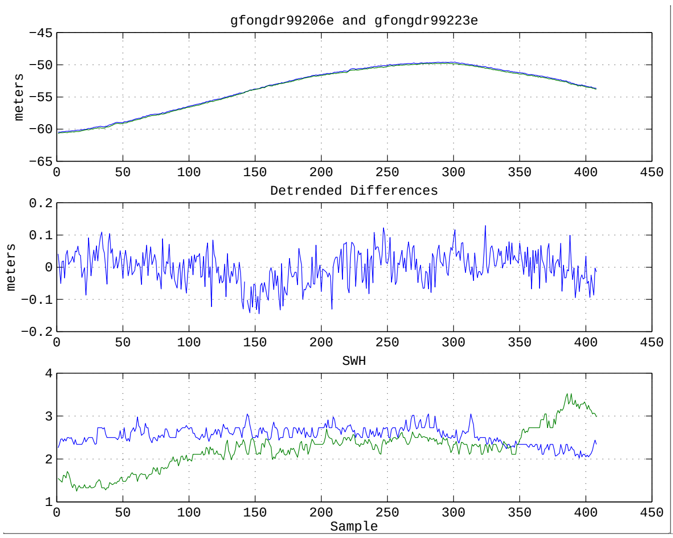
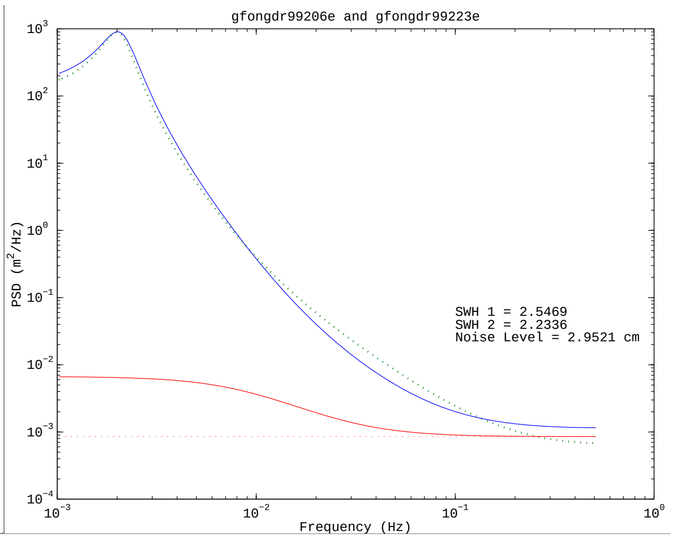
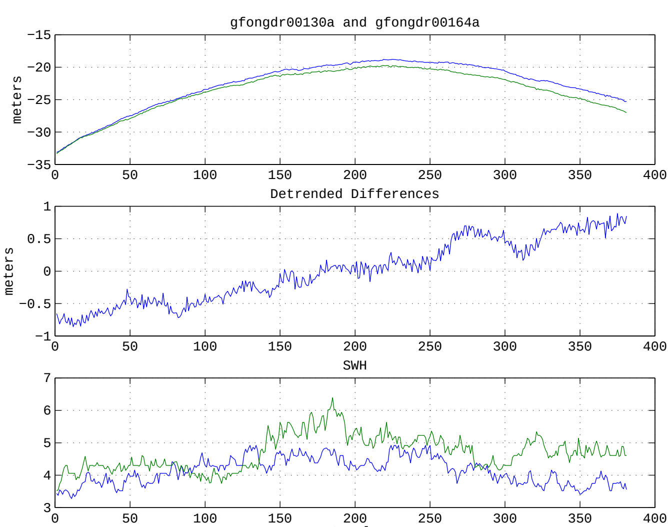
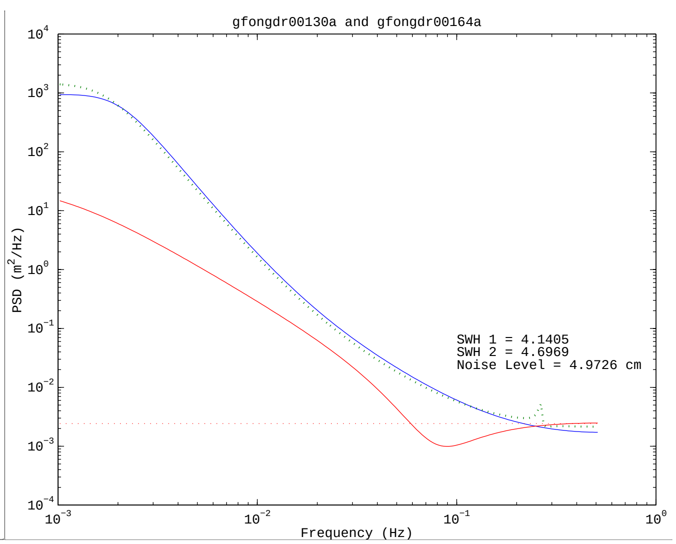
meters
Detrended Differences
meters
SWH
Sample

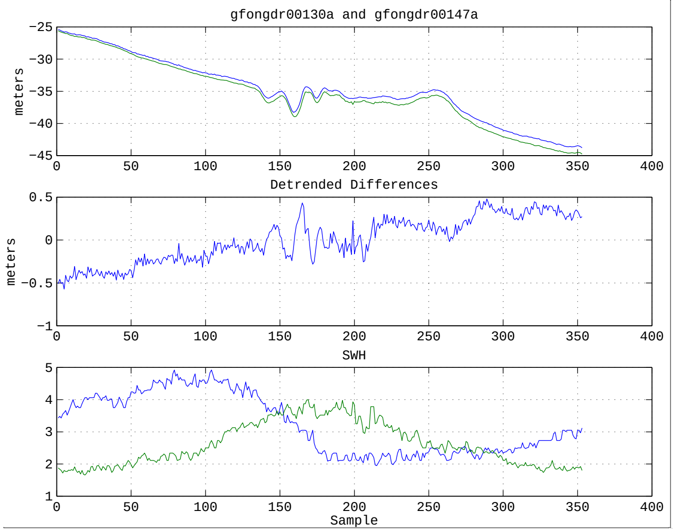

gfongdr99206d and gfongdr99223d
PSD (m^2/Hz)
SWH 1 = 4.7556
SWH 2 = 4.1407
Noise Level = 5.0187 cm
Frequency (Hz)

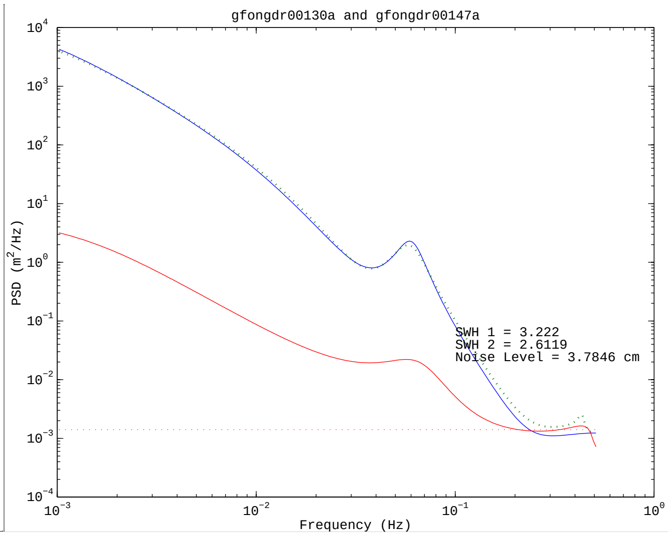

gfongdr99206e and gfongdr99223e
meters
Detrended Differences
meters
SWH
Sample

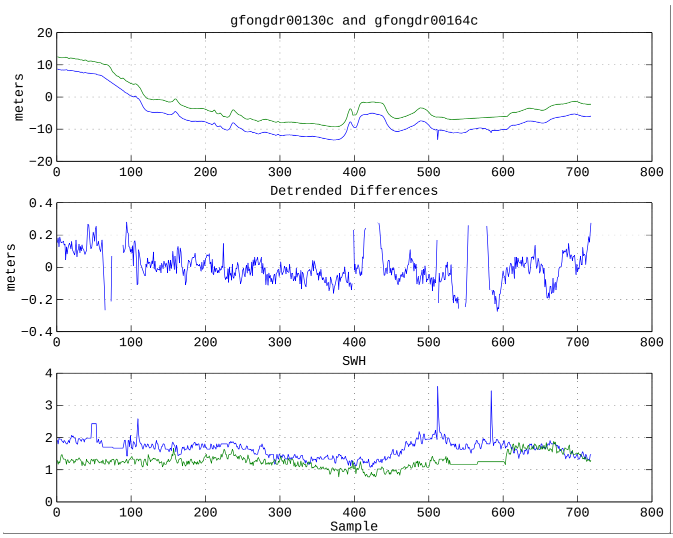

gfongdr99206e and gfongdr99223e
PSD (m^2/Hz)
SWH 1 = 2.5469
SWH 2 = 2.2336
Noise Level = 2.9521 cm
Frequency (Hz)

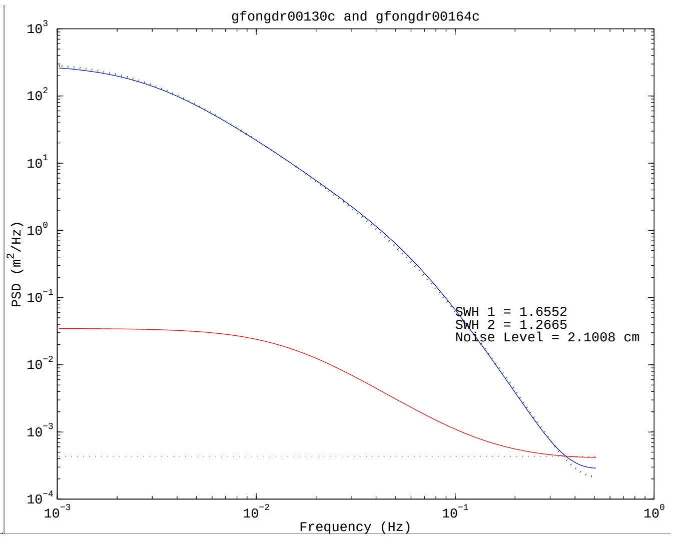

gfongdr00130a and gfongdr00164a
meters
Detrended Differences
meters
SWH
Sample

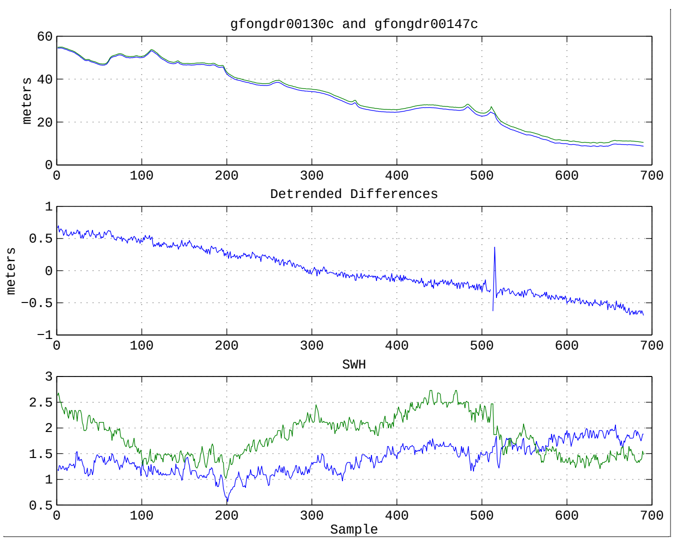

gfongdr00130a and gfongdr00164a
PSD (m^2/Hz)
SWH 1 = 4.1405
SWH 2 = 4.6969
Noise Level = 4.9726 cm
Frequency (Hz)

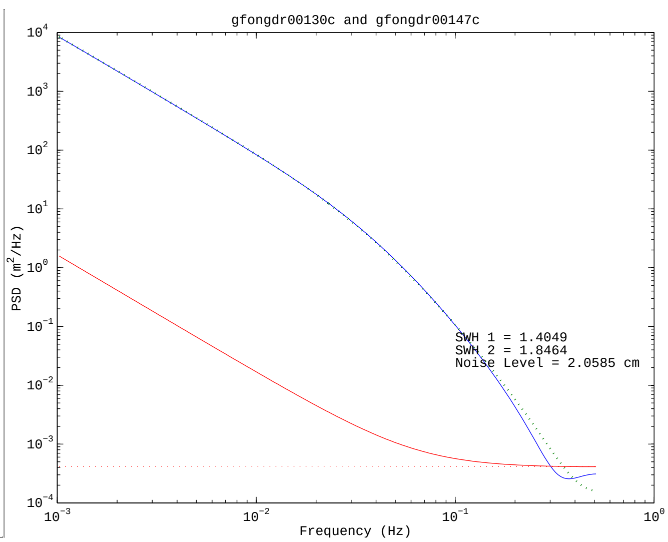

gfongdr00130a and gfongdr00147a
meters
Detrended Differences
meters
SWH
Sample

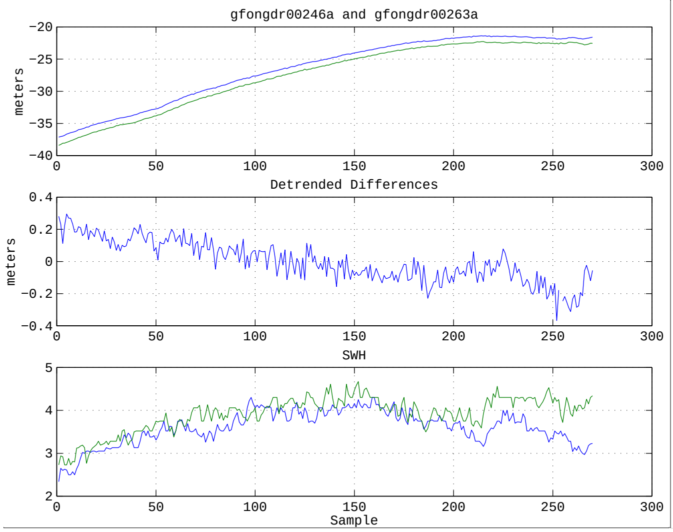
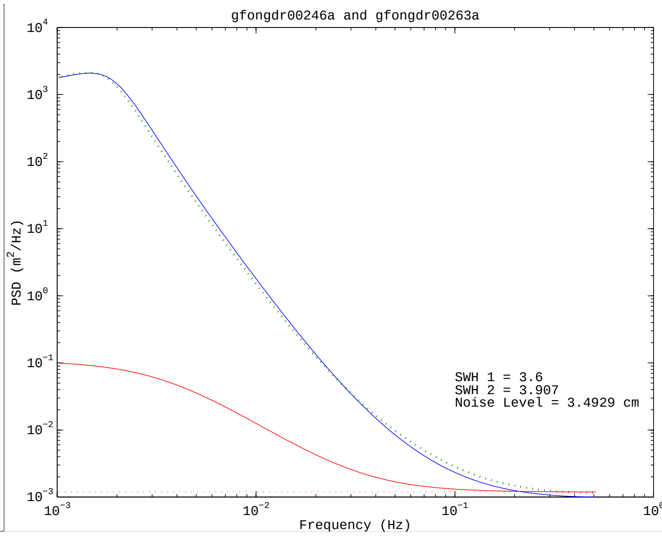
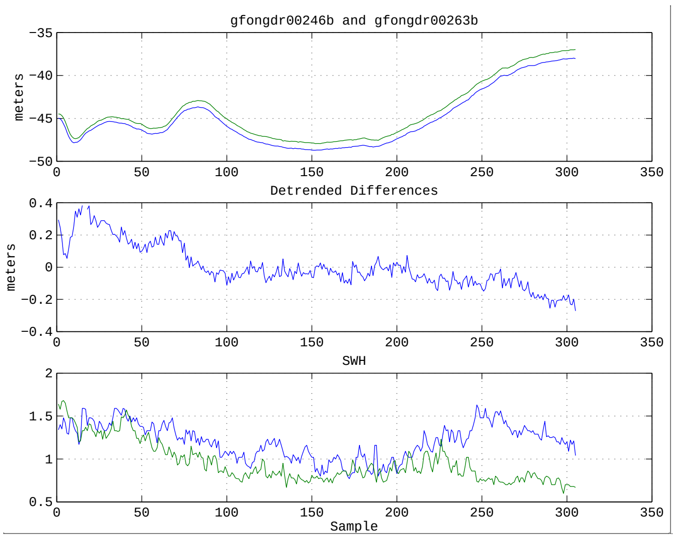
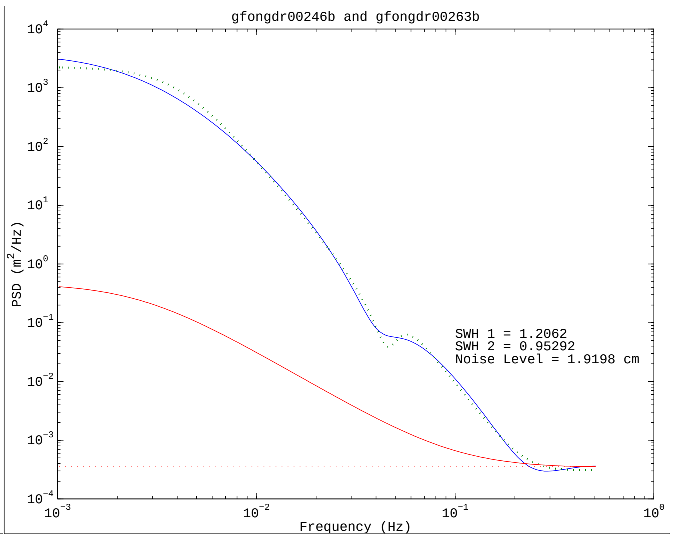
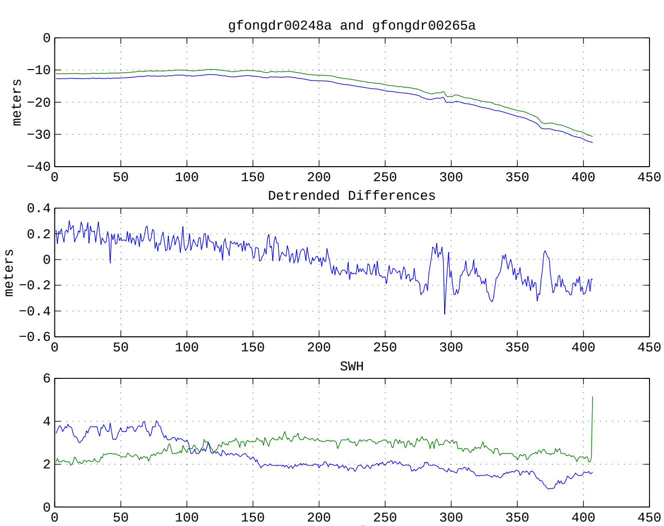
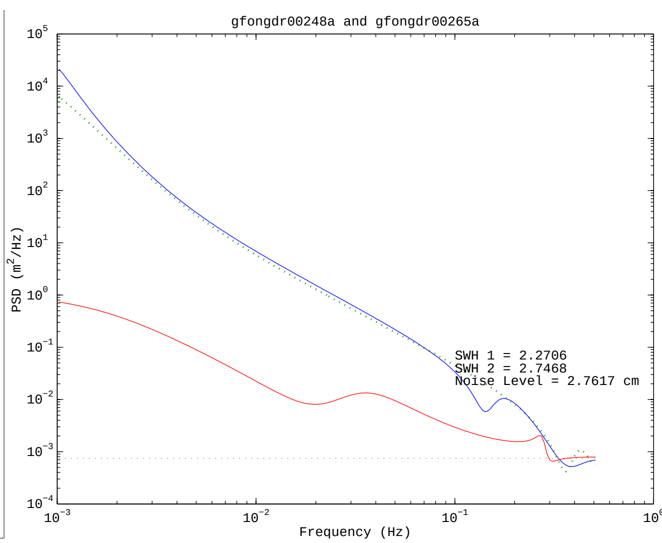

gfongdr00130a and gfongdr00147a
PSD (m^2/Hz)
SWH 1 = 3.222
SWH 2 = 2.6119
Noise Level = 3.7846 cm
Frequency (Hz)

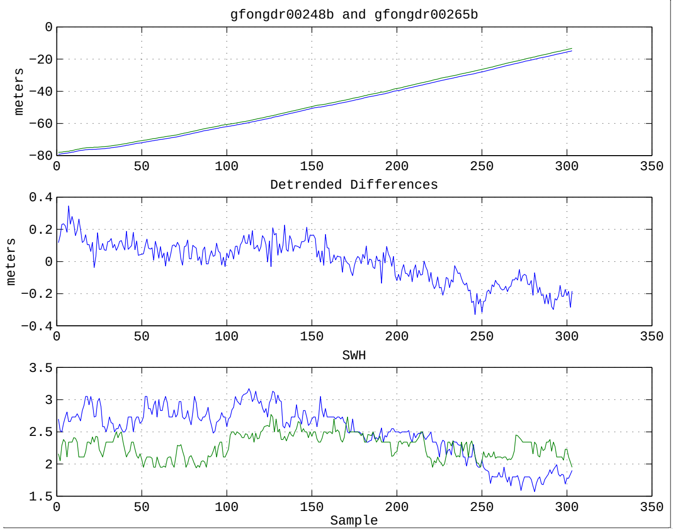

gfongdr00130c and gfongdr00164c
meters
Detrended Differences
meters
SWH
Sample

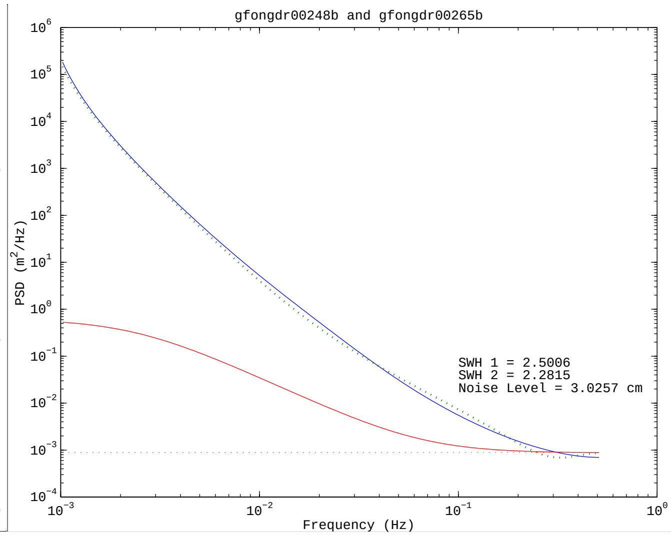

gfongdr00130c and gfongdr00164c
PSD (m^2/Hz)
SWH 1 = 1.6552
SWH 2 = 1.2665
Noise Level = 2.1008 cm
Frequency (Hz)

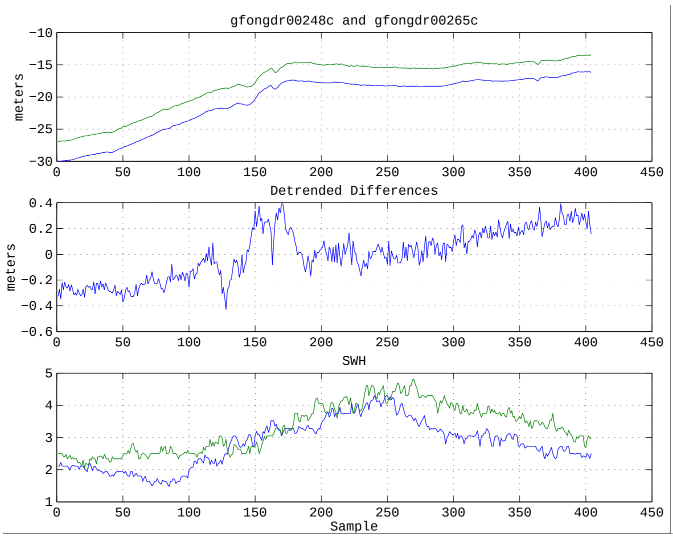

gfongdr00130c and gfongdr00147c
meters
Detrended Differences
meters
SWH
Sample

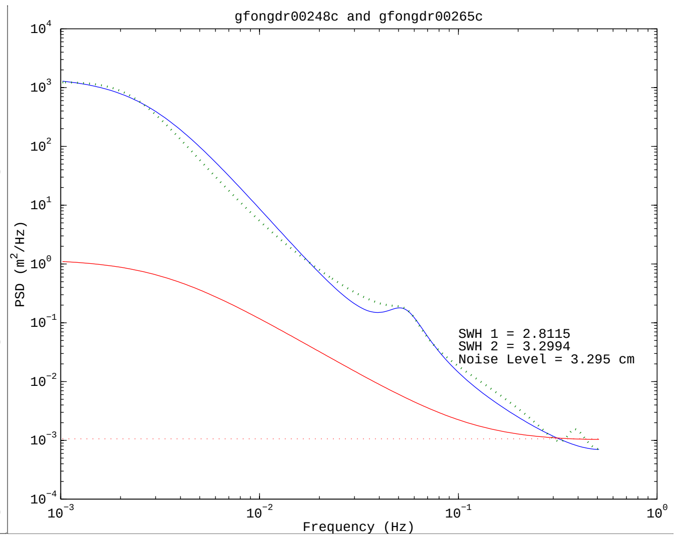

gfongdr00130c and gfongdr00147c
PSD (m^2/Hz)
SWH 1 = 1.4049
SWH 2 = 1.8464
Noise Level = 2.0585 cm
Frequency (Hz)

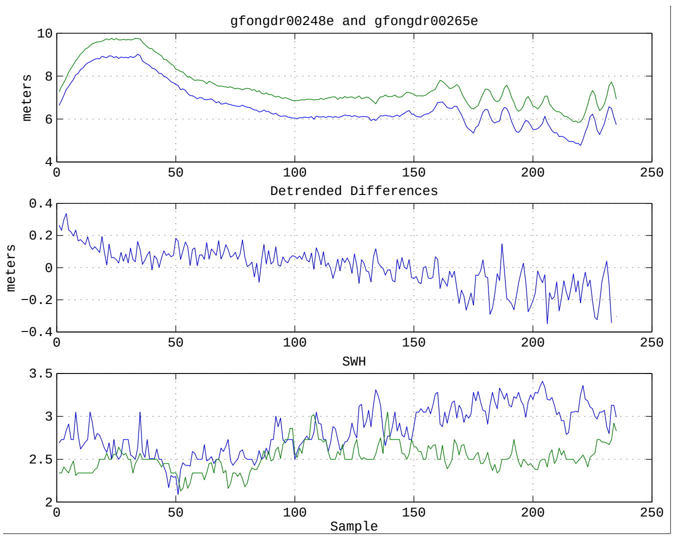

gfongdr00246a and gfongdr00263a
meters
Detrended Differences
meters
SWH
Sample

gfongdr00246a and gfongdr00263a
PSD (m^2/Hz)
SWH 1 = 3.6
SWH 2 = 3.907
Noise Level = 3.4929 cm
Frequency (Hz)

gfongdr00246b and gfongdr00263b
meters
Detrended Differences
meters
SWH
Sample

gfongdr00246b and gfongdr00263b
PSD (m^2/Hz)
SWH 1 = 1.2062
SWH 2 = 0.95292
Noise Level = 1.9198 cm
Frequency (Hz)

gfongdr00248a and gfongdr00265a
meters
Detrended Differences
meters
SWH
Sample

gfongdr00248a and gfongdr00265a
PSD (m^2/Hz)
SWH 1 = 2.2706
SWH 2 = 2.7468
Noise Level = 2.7617 cm
Frequency (Hz)

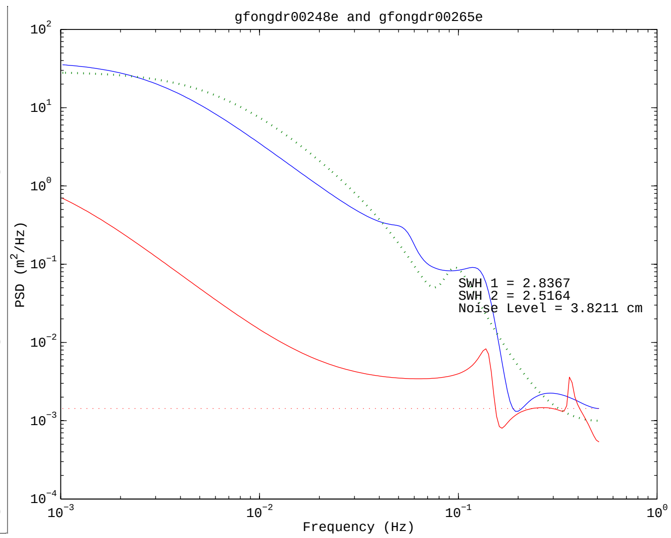

gfongdr00248b and gfongdr00265b
meters
Detrended Differences
meters
SWH
Sample

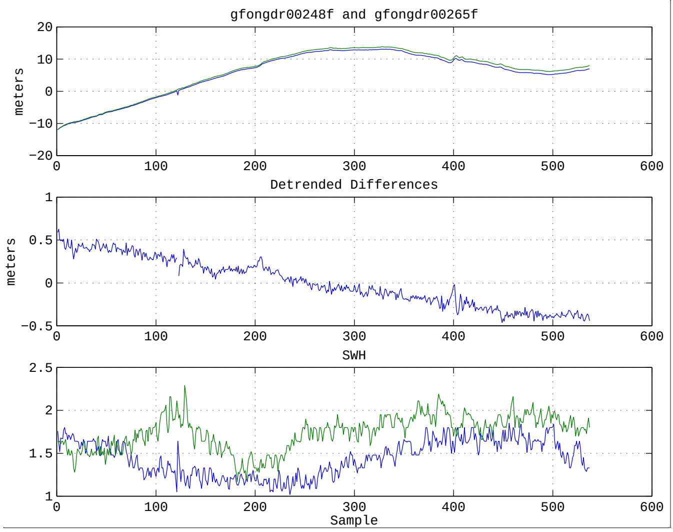

gfongdr00248b and gfongdr00265b
PSD (m^2/Hz)
SWH 1 = 2.5006
SWH 2 = 2.2815
Noise Level = 3.0257 cm
Frequency (Hz)

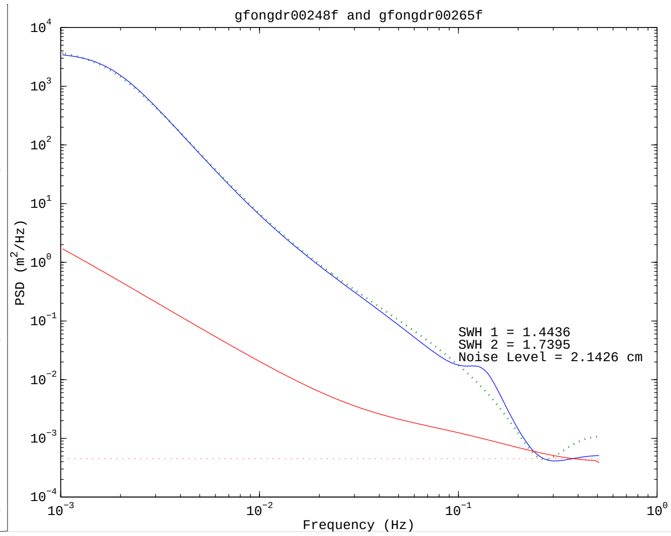

gfongdr00248c and gfongdr00265c
meters
Detrended Differences
meters
SWH
Sample

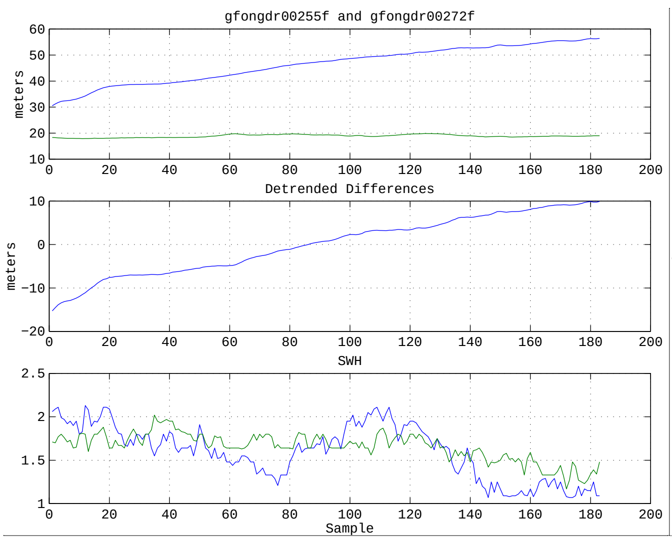

gfongdr00248c and gfongdr00265c
PSD (m^2/Hz)
SWH 1 = 2.8115
SWH 2 = 3.2994
Noise Level = 3.295 cm
Frequency (Hz)

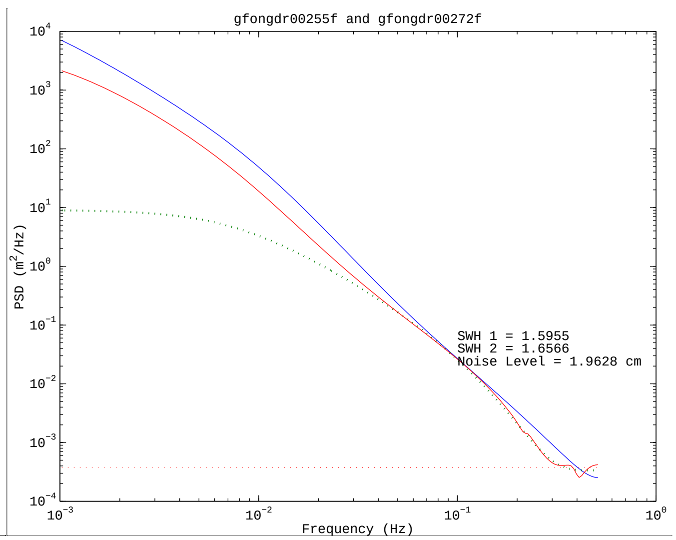

gfongdr00248e and gfongdr00265e
meters
Detrended Differences
meters
SWH
Sample

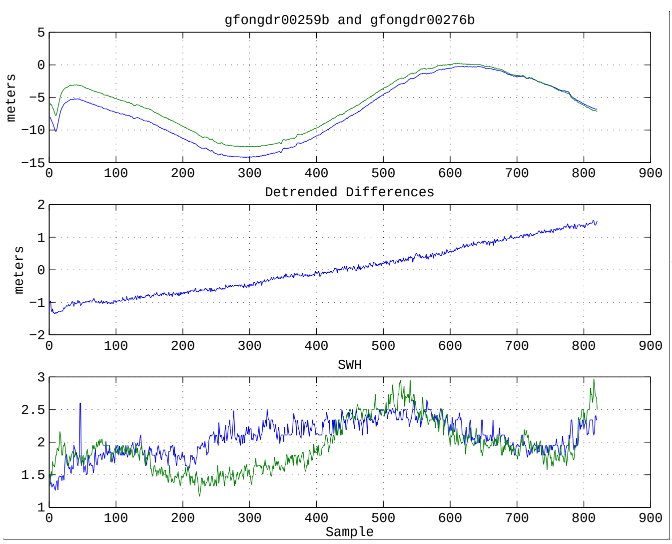

gfongdr00248e and gfongdr00265e
PSD (m^2/Hz)
SWH 1 = 2.8367
SWH 2 = 2.5164
Noise Level = 3.8211 cm
Frequency (Hz)

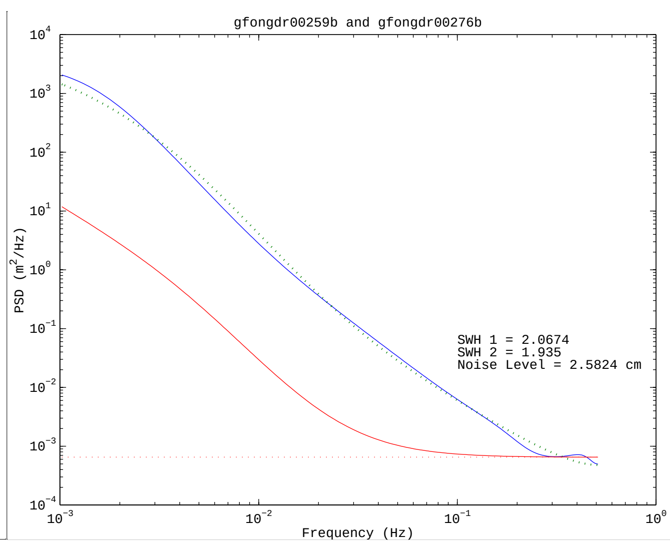

gfongdr00248f and gfongdr00265f
meters
Detrended Differences
meters
SWH
Sample

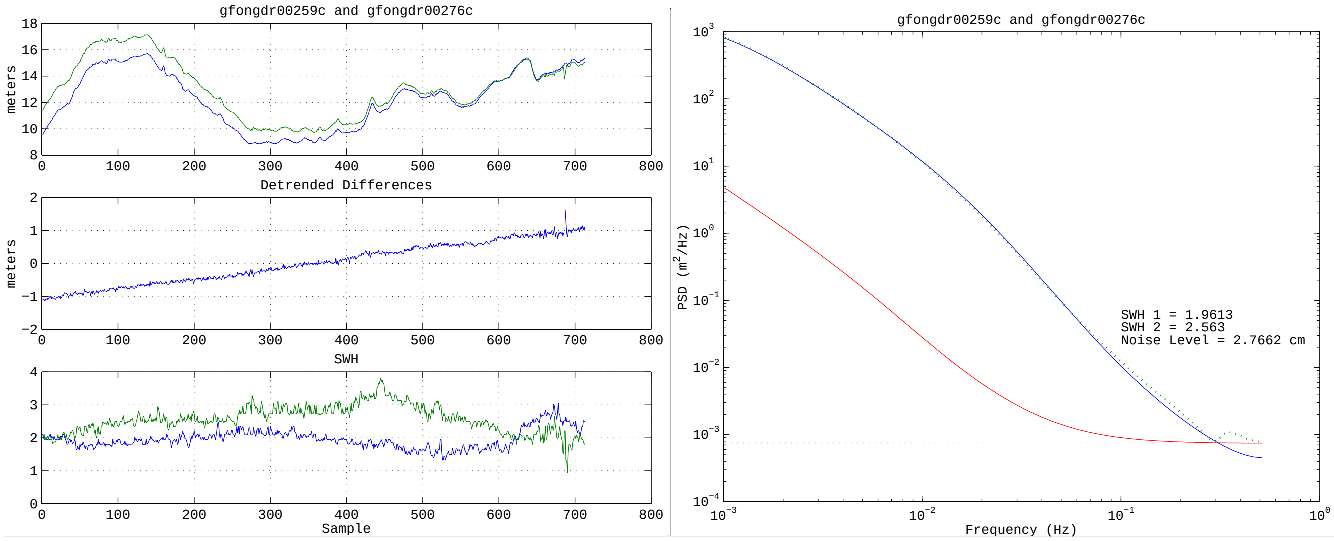

gfongdr00248f and gfongdr00265f
PSD (m²/Hz)
SWH 1 = 1.4436
SWH 2 = 1.7395
Noise Level = 2.1426 cm
Frequency (Hz)

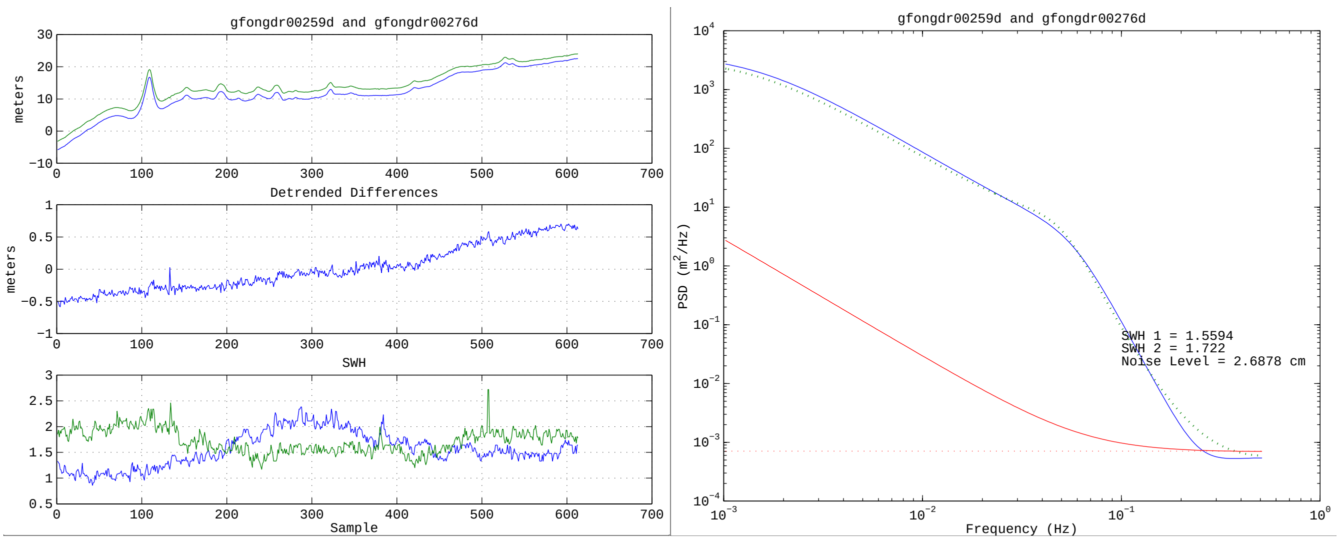

gfongdr00255f and gfongdr00272f
meters
Detrended Differences
meters
SWH
Sample


gfongdr00255f and gfongdr00272f
PSD (m²/Hz)
SWH 1 = 1.5955
SWH 2 = 1.6566
Noise Level = 1.9628 cm
Frequency (Hz)


gfongdr00259b and gfongdr00276b
meters
Detrended Differences
meters
SWH
Sample


gfongdr00259b and gfongdr00276b
PSD (m²/Hz)
SWH 1 = 2.0674
SWH 2 = 1.935
Noise Level = 2.5824 cm
Frequency (Hz)


gfongdr00259c and gfongdr00276c
meters
Detrended Differences
meters
SWH
Sample
gfongdr00259c and gfongdr00276c
PSD (m^2/Hz)
SWH 1 = 1.9613
SWH 2 = 2.563
Noise Level = 2.7662 cm
Frequency (Hz)


gfongdr00259d and gfongdr00276d
meters
Detrended Differences
meters
SWH
Sample
gfongdr00259d and gfongdr00276d
PSD (m^2/Hz)
SWH 1 = 1.5594
SWH 2 = 1.722
Noise Level = 2.6878 cm
Frequency (Hz)

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